CARBON NANOTUBE BASED NEMS AND MODELING

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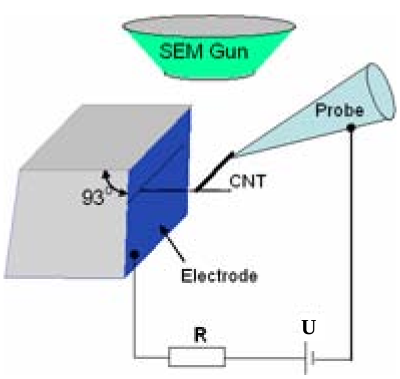
Abstract

Carbon nanotube based nanoelectromechanical systems (NEMS) are nanofabricated and tested. *In-situ* scanning electron microscopy (SEM) measurements of the deflection of the cantilever under electrostatic-actuation are reported. In particular, a cantilever nanotube suspended over an electrode (nanoswitch), from which a differential in electrical potential is imposed, is studied. The finite deformation regime here investigated is the first of its kind. An electromechanical analysis of the characteristics of the device is used to interpret the measurement. The model includes the concentration of electrical charge, at the end of the nanocantilever, finite kinematics and the van der Waals force. The results reported in this work are particularly useful in the characterization of the electro-mechanical properties of nanotubes as well as in the optimal design of nanotube based NEMS devices.

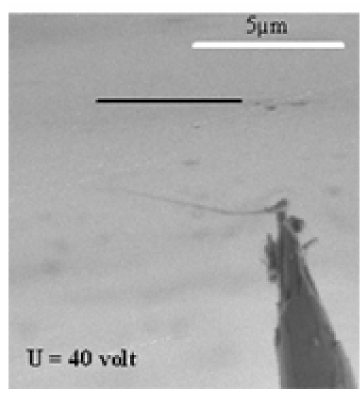
INTRODUCTION

Carbon nanotubes (CNTs) have long been considered ideal building blocks for Nanoelectromechanical systems (NEMS) due to their superior electro-mechanical properties. The CNT-based NEMS reported in the literature, such as nanotweezers,[1] and feedback-controlled nanocantilever NEMS devices,[2] can be simply modeled as CNT cantilevers hanging over an infinite conductive substrate. In order to design a functional NEMS device, its electro-mechanical characteristic should be well quantified in advance. Generally, multi-walled carbon nanotubes (MWNTs) can be modeled as homogeneous cylindrical beams and perfect conductors. In this paper, we investigate the electro-mechanical characteristics of CNT-based NEMS devices by in-situ scanning electron microscopy (SEM) measurement and electromechanical analysis. In particular, a cantilever nanotube suspended over an electrode (nanoswitch), from which a differential in electrical potential is imposed, is studied.

EXPERIMENT



(a)



(b)

Figure* 1 *(a) Schematic of the experimental configuration employed in the electrostatic actuation of MWNTs. (b) SEM image of the deformed carbon nanotube cantilever at biased voltage U = 40 volt.

The *in-situ* electrostatic actuation of CNT cantilever is illustrated in Fig. 1(a).[3] A MWNT with length 6.8 μm, welded to a 3D manipulator probe by nanomanipulation and electron beam induced deposition (EBID) of platinum (Pt), was placed horizontal and parallel to the electrode, which is a piece of Si wafer coated with Au film attached to a Teflon block. By focusing on the electrode surface and adjusting the working distance to be the same to that of nanotube, a feature on the electrode, which is on the same horizontal plane with the nanotube was located. Such feature is schematically marked as a line in Fig. 1 (a). The horizontal distance between the nanotube and the line was controlled by the nanomanipulator and set to 3 µm. Because the ratio between the length of the nanotube and the gap between the nanotube and electrode is 2.3, the deflection of the nanotube under electrostatic force can be considered to be in the finite kinematics regime. With the increase of the applied voltage, the deflection of the nanotube increased and the local curvature became substantial. Fig 1 (b) shows the scanning electron images of the deflection of the carbon nanotube when applied voltages U = 40 volts. The feature on the electrode, which is in the same horizontal plane containing the cantilever nanotube, is schematically marked as a solid black line in Fig. 1(b). The deflection and local curvature of the deflected nanotube can be clearly observed. The pull-in voltage of the nanotube cantilever device was measured to be about 48 volts.

MODELING

The governing equation of the nanotube cantilever under finite kinematics (just considering bending), is

$$EI\frac{d^2}{dx^2}\left(\frac{d^2w}{dx^2}\left(1+\left(\frac{dw}{dx}\right)^2\right)^{-\frac{3}{2}}\right)=\left(q_{vdw}+q_{elec}\right)\sqrt{1+\left(\frac{dw}{dx}\right)^2} \qquad (1)$$

where E is the Young Modulus, I is the moment of the inertia of the nanotube, w is the deflection of the nanotube, x is the axis along the nanotube. q_{vdw} is the van der Waals force which can be evaluated by the method reported by Desquence, et al.,[4] q_{elec} is the electrostatic force, which can be computed by the capacitance method. The capacitance per unit length along the cantilever nanotube is approximated as[5]

$$C=C_d\left(r(x)\right)\left\{1+0.85\left[(H+R)^2 R\right]^{1/3}\delta\left(x-x_{tip}\right)\right\} \qquad (2)$$

where the first term in the bracket accounts for the uniform charge along the side surface of the tube and the second term accounts for the concentrated charge at the end of the tube. $x=x_{tip}\neq L$, as a result of the finite kinematics. $\delta(x)$ is the Dirac distribution function, $R=R_{ext}$ is the external radius of the nanotube and H is the initial distance between the low fiber of nanotube and the ground. $C_d(r)$ is the distributed capacitance along the side surface per unit length which is given by $C_d(r)=2\pi\varepsilon_0/a\cosh(1+r/R_{ext})$, where r is the distance between the lower fiber of the nanotube and the substrate, and ε_0 is the permittivity of vacuum.

RESULT AND DISCUSSION

The comparison between experimental data and the theoretical predictions shows they are in good agreement. For the theoretical predictions, the following parameters were employed: L = 6.8 µm, H = 3 µm, $R=R_{ext}$ = 23.5 nm, E = 1 TPa. The computed pull-in voltage is 47.8 Volts, which matches the experimentally measured value 48 Volts very well. The results from the modeling reveal that, of all the effects contributing to the deformation and pull-in of the device, the concentration of charge at the end of the cantilever was identified as the most dominant, with an error of 13.4 % when its effect is omitted. The finite kinematics effect is less pronounced, with an error of 7.0 % when neglected. These errors were computed for the geometry and material examined in our experiments.

The methodologies reported here are completely general and as such are expected to be useful in the characterization of electro-mechanical properties of nanotubes and nanowires, as well as in the optimal design of nanotube based NEMS devices.

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